AIP Advances

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Citation: AIP Advances **1**, 041903 (2011); doi: 10.1063/1.3676168
View online: http://dx.doi.org/10.1063/1.3676168
View Table of Contents: http://aipadvances.aip.org/resource/1/AAIDBI/v1/i4
Published by the American Institute of Physics.

AIP ADVANCES **1**, 041903 (2011)

On chip complex signal processing devices using coupled phononic crystal slab resonators and waveguides

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(Received 11 November 2011; accepted 19 December 2011; published online 29 December 2011; corrected 10 January 2012)

In this paper, we report the evidence for the possibility of achieving complex signal processing functionalities such as multiplexing/demultiplexing at high frequencies using phononic crystal (PnC) slabs. It is shown that such functionalities can be obtained by appropriate cross-coupling of PnC resonators and waveguides. PnC waveguides and waveguide-based resonators are realized and cross-coupled through two different methods of mechanical coupling (i.e., direct coupling and side coupling). Waveguide-based PnC resonators are employed because of their high-Q, compactness, large spurious-free spectral ranges, and the possibility of better control over coupling to PnC waveguides. It is shown that by modifying the defects in the formation of the resonators, the frequency of the resonance can be tuned. *Copyright 2011 Author(s). This article is distributed under a Creative Commons Attribution 3.0 Unported License*. [doi:10.1063/1.3676168]

I. INTRODUCTION

Micro/nano-mechanical (MM) structures made of silicon (Si) are getting increased attention in communications and sensing due to their small form factors, compatibility with microelectronic and photonic technologies, flexibility and maturity of fabrication, and good mechanical characteristics.[1] Besides their widespread applications in elements with moving parts (e.g., switches,[2] accelerometers, and gyroscopes),[3] on-chip MM devices based on small mechanical vibrations[4] (such as front-end filters, oscillators, and sensing elements) are proving to be the technology of choice when high quality factors and more functionalities at moderately high frequencies are of demand.

More recently, phononic crystals (PnCs),[5,6] which are artificially-made structures with periodic variations in their mechanical properties, have demonstrated valuable capabilities in controlling mechanical vibrations at micro and nano scales.[7–9] Phononic band gaps (PnBGs), i.e., ranges of frequencies in which mechanical vibration (or phonons) are not allowed to propagate, can be obtained in PnCs. Creating defects in PnCs within PnBGs makes it possible to effectively store or guide mechanical vibrations. Recently, micro/nano-fabricated PnC structures have been developed to support PnBGs for all propagating modes and propagation directions. Especially, PnCs composed of a hexagonal (or honeycomb) array of air cylinders embedded in a single-crystal Si slab have been demonstrated to show very large band gaps at VHF frequencies without imposing fabrication difficulties.[8] The range of operation of such PnC slab structures can be extended to even higher (of the order of GHz) frequencies by scaling down the features, while most of the procedures, methods, and arguments will remain true. These structures have been shown to be very effective in confining elastic energy. In fact, very high quality factor resonators and low-loss waveguides have been realized by creating defects in the PnC structure.[10,11] It is also shown that using the developed structures, support loss, which is an important source of loss in MM resonators especially at high frequencies, can be suppressed.[12]

Complex functionalities, such as multiplexing, demultiplexing, and multi-channel filtering are of great demand at high frequencies in communications and multi-analyte sensing elements. Developing such functions is, therefore, of great interest using PnC structures with high frequency PnBGs due to

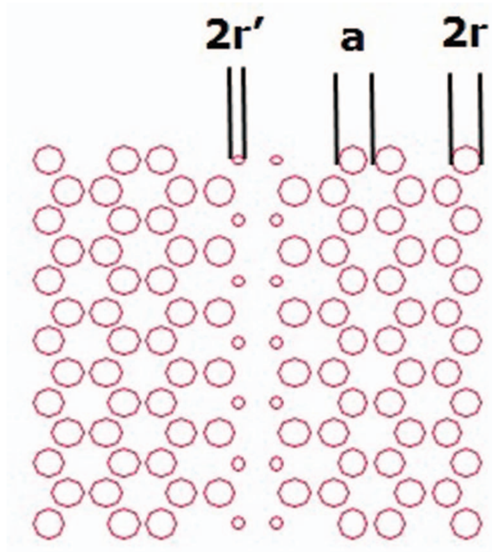

FIG. 1. Schematic of the top view of the PnC slab structure waveguide made by reducing the diameter of two rows of holes.

their unique, unprecedented capabilities. An effective means of implementing such complex signal processing functionalities may be done through the use of coupled resonators and waveguides. Exemplarily, filters with sharp transition regions have been designed and simulated by an array of coupled PnC slab resonators.[13]

In this paper, we report the design, fabrication, and characterization of different VHF resonators communicating through a PnC waveguide to demonstrate the possibility of high-frequency multiplexing/demultiplexing using PnC structures in an appropriate platform. Waveguide-based resonators[14,15] are employed because of their high-Q, compactness, large spurious-free spectral ranges and the possibility of better control over coupling to waveguides with similar structure. The desired extensional signals are selectively excited by a piezoelectric stack fabricated on top of the resonators.[16] This demonstration evidences the possibility of realizing compact high-frequency signal processing devices such as filter banks using PnC platforms through an appropriate resonator/waveguide coupling architecture.

II. THE DESIGN

The designed PnC structure (shown in Figure 1) is composed of a hexagonal (honeycomb) array of air cylinders embedded in a free-standing Si slab. The spacing between the centers of the nearest holes (a), as well as the thickness of the slab (d) is 15 μm, and the diameter of the holes ($2r$) is approximately 12.5 μm (i.e., $2r \approx 0.83a$). Such a PnC structure supports a large complete PnBG in the frequency window of 117 MHz $< f <$ 149 MHz,[7] which is appropriate for wide-band applications. A waveguide is realized by reducing the diameter ($2r'$) of two rows of holes to 4.9 μm (i.e., $2r' \approx 0.33a$) in the PnC structure as shown in Figure 1.[15]

The PnC waveguide shown in Figure 1 can be terminated at the two ends with perfect PnC structure to form a Fabry-Perot type resonator.[15] Such a resonator can be coupled to a bus PnC waveguide from one end (Figure 2(a)), or from the side (Figure 2(b)). The resonance frequency of the resonator can be tuned by changing the diameter of the two rows of holes adjacent to the defect as shown in Figure 2(c).

Two waveguide-based resonators are designed with 11 periods in the direction of the waveguide to resonate at two different frequencies. The resonance frequencies are chosen so that a common extensional mode is used between the waveguide and the resonators, so that coupling between the resonators and waveguides would be readily possible. Such waveguide-based resonators have shown extensional resonances at frequencies inside the PnBGs with high-Qs as the support loss is naturally

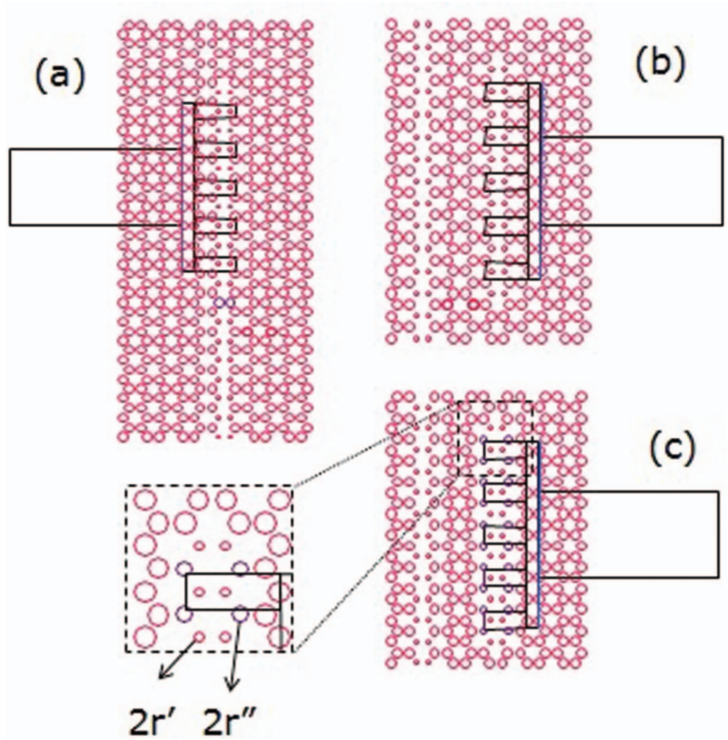

FIG. 2. Schematic of 11-period waveguide-based PnC slab resonators (a) end-coupled to a bus waveguide with a similar structure, and (b) side-coupled to the bus waveguide; (c) waveguide-based PnC resonator with a different frequency of resonance side-coupled to the bus waveguide. Transducer electrodes are fabricated on top of the resonators to excite the resonators. (The inset shows a magnified schematic of one electrode finger of (c) with diameters of the reduced holes specified).

suppressed in the structure. Exemplarily, Qs of the order o 14000 at frequencies around 130 MHz are obtained that are superior compared to the state of the art architectures with a similar stack of layers.[15]

To excite and detect the desired modes, transducers are fabricated by sandwiching a thin (∼1 μm) layer of sputtered piezoelectric aluminum nitride (AlN) between two layers of molybdenum (Mo). Electrical signals are transformed back and forth into mechanical energy through the vertical electric field between the two electrode layers. The top metallic fingers are formed based on the mode of resonance to provide appropriate selective coupling of the intended extensional modes.[16]

To evaluate the possibility of communication between the resonators, we designed a three-port device. A top-view schematic of the designed device is shown in Figure 3. The resonators at Ports 1 and 3 have similar structures to the bus waveguide and are made by reducing the radius of two adjacent rows of holes for 11 periods of the PnC (a=d=15μm, 2r = 12.5 μm, 2r'=4.9 μm). The mechanisms of coupling to the bus waveguide, however, are different for the two resonators. The resonator at Port 3 is directly coupled to the waveguide by one row of holes separation in the waveguide direction as is demonstrated in Figure 2(a). However, the resonator at Port 1 is side-coupled to the waveguide by placing the resonator one PnC period apart from the waveguide as shown in Figure 2(b). The resonator at Port 2 is also side-coupled to the waveguide and is placed at the same distance as the resonator at Port 1 from the waveguide. However, in the resonator at Port 2 (see Figure 2(c)), two additional rows of holes adjacent to the defect are also slightly reduced in diameter to shift the frequency of the resonance of the resonator from that of Resonators 1 and 3 (2r′=4.9 μm and 2r″= 9 μm).

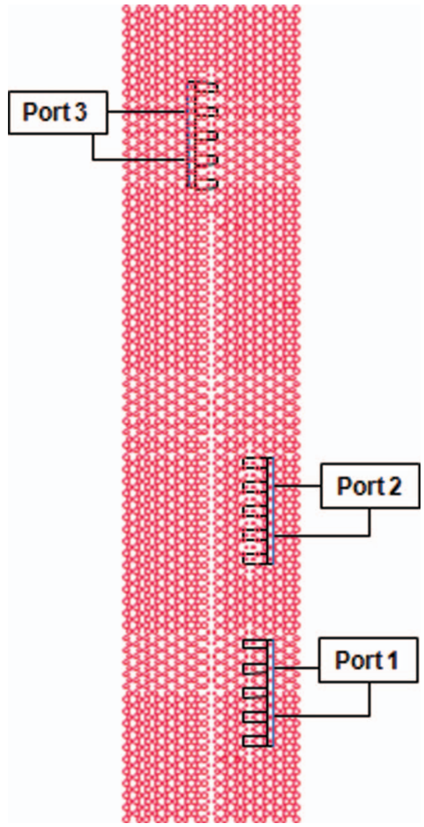

FIG. 3. Top view schematic of the designed structure.

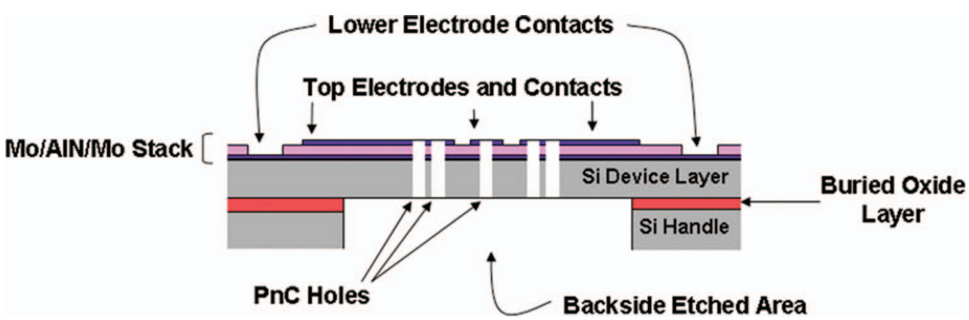

FIG. 4. Lateral Profile of the stack of layers in the designed structure.

III. FABRICATION

The structure is fabricated using a post-CMOS compatible fabrication process using a high-resistivity silicon on insulator (SOI) wafer with a 15μm device layer, a 2μm buried oxide (BOX) layer and a 400μm handle layer. A 100nm/1μm/100nm stack of Mo/AlN/Mo is sputtered on top of the device layer to serve as the transducer. The top Mo layer and the AlN layers are patterned on the desired locations followed by etching of the PnC holes through the device layer. The device is then released by deep plasma etching of the handle and the BOX layers after backside alignment and lithography. A schematic of the cross section of the stack of layers including the piezoelectric and PnC device layers can be seen in Figure 4.

The top view scanning electron microscope (SEM) images of the fabricated structure are shown in Figure 5.

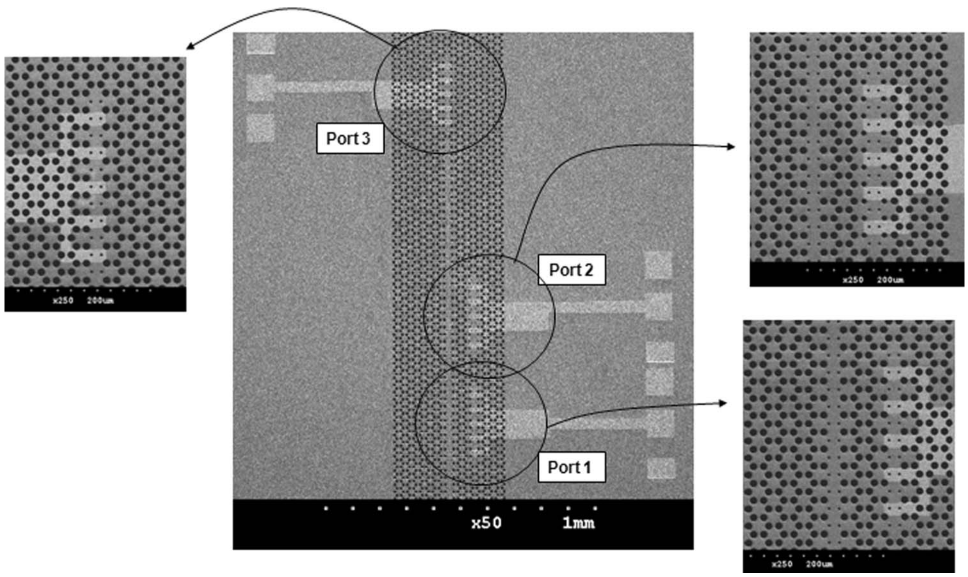

FIG. 5. SEM images of the fabricated structure showing the device as well as individual resonator ports.

IV. CHARACTERIZATION

The structure is characterized using a vector network analyzer for the frequencies of interest within the PnBG of the PnC slab structure. Two-port scattering parameters of Ports 3 and 1, and then those of the Ports 3 and 2 are measured. Figure 6(a) and Figure 6(b) show self scattering parameters of the three ports, while Figure 6(c) and Figure 6(d) show the cross-scattering parameters of the two cross-coupled ports. As shown in Figure 6(a) and Figure 6(b), a sharp dip in the self scattering parameters is observed at the intended resonance frequency of each of the resonators.

As can be seen in this figure, the frequency of resonance of the Ports 1 and 3 resonators are similarly located at $f_{r1}= f_{r3} \sim 133$ MHz, while the resonance frequency of the Port 2 resonator is shifted by ∼1 MHz and is located at $f_{r2\sim}$ 134 MHz. As expected, since the resonance frequencies of the Ports 1 and 3 resonators match, a peak is observed in the transmission parameter between Ports 1 and 3, while the transmission profile between Ports 3 and 2 is at the noise level. This is despite the fact that the distance between Ports 3 and 2 is less than the distance between Ports 3 and 1. This shows the independence of the operation of the resonators at different frequencies of resonance despite their proximity and a direct evidence for the feasibility of forming compact PnC-based resonance multiplexing/demultiplexing and selective filtering. Thus, the proposed PnC platform can be used to form complex signal processing functionalities on chip.

V. CONCLUSIONS

In this paper, we showed that PnC slab waveguides and waveguide-based resonators can serve as an appropriate platform for performing complex signal processing functions. The results presented in this paper show that PnC slab resonators can be coupled to a waveguide through different coupling schemes, and the resonators tuned at the same frequency can communicate by means of an acoustic signal through an appropriately designed PnC waveguide. The cross coupling between the resonators at different resonance frequencies is, however, negligible. This observation evidences the possibility of realizing complex signal processing functionalities, such as multiplexing/demultiplexing and multi-channel filtering at high frequencies through the use of coupled PnC resonators and waveguides.

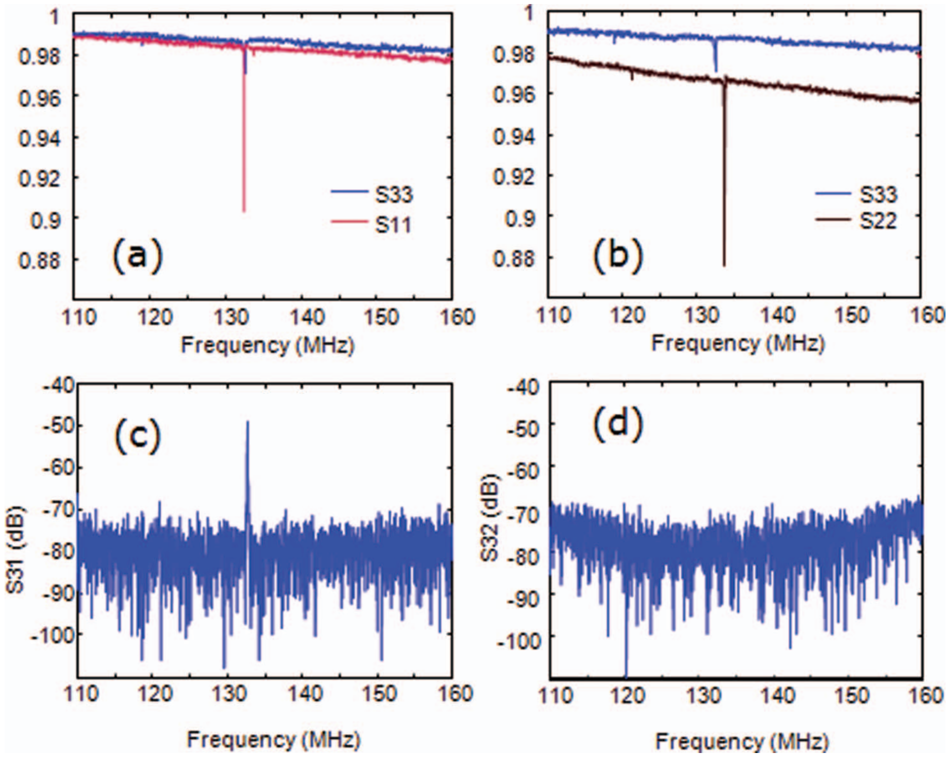

FIG. 6. Measured scattering parameters of the three port device of Figure 5.

ACKNOWLEDGMENT

The authors wish to thank the staff at Georgia Tech Microelectronics Research Center for their support in maintaining the fabrication equipment, Prof. Reza Abdolvand for his input on the fabrication, Prof. W. D. Hunt for providing the lab equipment. This work was supported by the National Science Foundation under Contract Number ECCS-0901800 (A. Weisshaar).

[1] K. E. Petersen, "Silicon as a mechanical material," Proceedings of the IEEE **70**, 420 (1982).
[2] E. R. Brown, "RF-MEMS switches for reconfigurable integrated circuits," IEEE Transactions on Microwave Theory and Techniques **46**, 1868, (1998).
[3] N. Yazdi, F. Ayazi, and K. Najafi, "Micromachined inertial sensors," Proceedings of the IEEE **86**, 1640 (1998).
[4] C. T.-C. Nguyen, L. P. B. Katehi, and G. M. Rebeiz, "Micromachined devices for wireless communications," Proceedings of the IEEE **86**, 1756 (1998).
[5] M. M. Sigalas, and E. N. Economou, "Elastic and acoustic wave band-structure," Journal of Sound and Vibration **158**, 377 (1992).
[6] M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, "Acoustic band-structure of periodic elastic composites," Physical Review Letters **71**,2022 (1993).
[7] S. Mohammadi, A. A. Eftekhar, A. Khelif, H. Moubchir, R. Westafer, W. D. Hunt, A. Adibi, "Complete phononic bandgaps and bandgap maps in two-dimensional silicon phononic crystal plates," Electronic Letters **43**, 898 (2007).
[8] S. Mohammadi, A. A. Eftekhar, A. Khelif, W. D. Hunt, and A. Adibi, "Evidence of large high-frequency complete phononic band gaps in silicon phononic crystal plates," Applied Physics Letters **92**, 2219051 (2008).
[9] Y. M. Soliman, M. F. Su, Z. C. Leseman, C. M. Reinke, I. El-Kady, and R. H. Olsson, "Phononic crystals operating in the gigahertz range with extremely wide band gaps," Applied Physics Letters **97**, 193502 (2010).
[10] S. Mohammadi, A. A. Eftekhar, W. D. Hunt, and A. Adibi, "High-Q micromechanical resonators in a two-dimensional phononic crystal slab," Applied Physics Letters **94**, 51903 (2009).
[11] S. Mohammadi, A. A. Eftekhar, W. D. Hunt, and A. Adibi, "Demonstration of large complete phononic band gaps and waveguiding in high-frequency silicon phononic crystal slabs," in *Proceedings of the 2008 IEEE International Frequency Control Symposium, 19-21 May 2008*, pp. 768-772.
[12] S. Mohammadi, A. Eftekhar, A. Khelif, and A. Adibi, "Support loss suppression in micromechanical resonators by the use of phononic band gap structures," in *Proceedings of the 2010 SPIE Photonics West*, 76090W (2010).

[13] A. Khelif, S. Mohammadi, A. A. Eftekhar, A. Adibi, and B. Aoubiza, "Acoustic confinement and waveguiding with a line-defect structure in phononic crystal slabs," Journal of Applied Physics **108**, 084515 (2010).
[14] S. Mohammadi, A. A. Eftekhar, and A. Adibi, "Support Loss-free Micro / Nano-mechanical Resonators using Phononic Crystal Slab Waveguides," in *Proceedings of the 2010 IEEE Frequency Control Symposium*, 521 (2010).
[15] S. Mohammadi and A. Adibi, "Waveguide-based phononic crystal micro/nano-mechanical high-Q resonators," Journal of Microelectromechanical Systems, DOI: 10.1109/JMEMS.2011.2174426, In Press.
[16] S. Mohammadi, A. A. Eftekhar, R. Pourabolghasem, and A. Adibi, "Simultaneous high-Q confinement and selective direct piezoelectric excitation of flexural and extensional lateral vibrations in a silicon phononic crystal slab resonator," Sensors and Actuators A: Physical **167**, 524 (2011).